Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar
Spanish Journal of Agricultural Research 2011 9(2), 597-605
ISSN: 1695-971-X
eISSN: 2171-9292

Selectivity and weed control efficacy of some herbicides applied to sprinkler irrigated rice (*Oryza sativa* L.)

J. Cavero[1]*, C. Zaragoza[2], A. Cirujeda[2], A. Anzalone[2], J. M. Faci[2] and O. Blanco[2]

[1] *Estación Experimental Aula Dei (CSIC). Apdo. 202. 50080 Zaragoza. Spain*
[2] *Centro de Investigación y Tecnología Agroalimentaria (DGA). Zaragoza. Spain*

Abstract

Sprinkler irrigation can reduce the irrigation water needed to grow rice. However, most available information on weed control with herbicides is related to flood irrigated rice because this is the main growing method. Field experiments were conducted at Zaragoza (Spain) during two years to study weed control and tolerance of sprinkler irrigated rice to several herbicides. The main weeds were *Atriplex prostrata* Bouchér ex DC., *Cyperus rotundus* L., *Echinochloa crus-galli* (L.) Beauv. and *Sonchus oleraceus* L. Rice cv Guadiamar was tolerant to preemergence (PRE) application of clomazone at 0.36 kg ha^{-1} and oxadiazon at 0.5 kg ha^{-1}. PRE application of pendimethalin at 1.32 kg ha^{-1} combined with clomazone at 0.36 kg ha^{-1} decreased rice yield. Postemergence (POST) application of bentazon at 1.6 kg ha^{-1} + MCPA at 0.25 kg ha^{-1} did not injure rice but POST application of azimsulfuron at 0.025 kg ha^{-1} produced visual crop injury. Only treatments that controlled grassy weeds since rice was planted and by more than 80% at harvest time lead to acceptable rice yield (> 5,000 kg ha^{-1}). Clomazone applied PRE at 0.36 kg ha^{-1} provided good control of grassy weeds (> 80%) and the highest rice yield, so it is recommended as a selective and efficacious PRE treatment for weed control of annual weeds in sprinkler irrigated rice. The perennial purple nutsedge was difficult to control at high plant densities (> 150 plants m^{-2}) and the recommended herbicide is azimsulfuron applied at POST at 0.02 kg ha^{-1}.

Additional key words: irrigation system; upland rice; weed competition.

Resumen

Selectividad de herbicidas y control de malas hierbas en arroz (*Oryza sativa* L.) regado por aspersión

El riego por aspersion puede reducir el riego necesario en arroz. Sin embargo, casi toda la información sobre control de malas hierbas con herbicidas se refiere a arroz inundado por ser la forma principal de cultivo. Se realizaron ensayos de campo durante dos años para estudiar el control de malas hierbas y la selectividad de diversos herbicidas en arroz regado por aspersión. Las principales malas hierbas fueron *Atriplex prostrata* Bouchér ex DC., *Cyperus rotundus* L., *Echinochloa crus-galli* (L.) Beauv. y *Sonchus oleraceus* L. El arroz cv Guadiamar toleró las aplicaciones en preemergencia (PRE) de clomazona a 0,36 kg ha^{-1} y de oxadiazón a 0,5 kg ha^{-1}. La aplicación en PRE de pendimetalina a 1,32 kg ha^{-1} combinada con clomazona a 0,36 kg ha^{-1} disminuyó el rendimiento del arroz. La aplicación en postemergencia (POST) de bentazona a 1,6 kg ha^{-1} + MCPA a 0,25 kg ha^{-1} no afectó al arroz, pero la aplicación en POST de azimsulfurón a 0,025 kg ha^{-1} produjo fototoxicidad visual. Solamente los tratamientos que controlaron más de un 80% las gramíneas desde la siembra del arroz hasta la cosecha obtuvieron rendimientos aceptables de arroz (> 5.000 kg ha^{-1}). La aplicación de clomazona en PRE a 0,36 kg ha^{-1} controló de forma eficaz las gramíneas (> 80%) y produjo los mayores rendimientos de arroz, recomendándose para el control de malas hierbas anuales en arroz regado por aspersión. La junquilla fue difícil de controlar a densidades altas (> 150 plantas m^{-2}), siendo el herbicida recomendado el azimsulfurón a 0,02 kg ha^{-1}.

Palabras clave adicionales: arroz no inundado; competencia de malas hierbas; sistema de riego.

* Corresponding author: jcavero@eead.csic.es
Received: 10-05-10; Accepted: 08-04-11.

Abbreviations used: POST (postemergence), PRE (preemergence), WAP (weeks after planting).

Introduction

Weed control is one of main cultural changes when rice is grown under sprinkler irrigation instead of under flood irrigation (Akkari *et al*., 1986; Battilani and Pietrosi, 1990; Spanu *et al*., 1992). Weed control in rice under flood irrigation is based on the existence of a water layer that precludes the growth of non-aquatic weed species, but allows the growth of aquatic or semiaquatic weeds, which results in a selection of the last type of weeds. Moreover, when grown under flood irrigation rice is usually not rotated with other crops, which makes weed control more difficult and costly herbicide treatments are required (Hill *et al*., 1994; Flórez *et al*., 1999; Rao *et al*., 2007).

Given the relevance of the rice crop worldwide, many studies of weed-crop competition and weed control have been conducted (Rao *et al*., 2007). However, most available information on weed control with herbicides is related to flood irrigated rice because this is the main growing method. In Spain there is not any relevant area grown under sprinkler irrigation. Worldwide irrigation of rice by sprinkler systems is only relevant in Brasil (Pinheiro *et al.*, 2006). Thus, there is limited information about the competition of weeds with rice and the selectivity and efficacy of herbicides when rice is grown under sprinkler irrigation (Akkari *et al*., 1986; Spanu *et al*., 1992). Some studies have been conducted on upland rice (Okafor and De Datta, 1976; Enyinnia, 1992; Esqueda, 2000), but this is mostly rainfed and not a fully irrigated crop.

In the absence of a standing water layer over the soil, no aquatic or semiaquatic weeds emerge (Spanu *et al*., 1992) and the weed species found in rice fields are the same as those appearing in other irrigated crops such as maize. Thus, strong competition occurs between rice and grass species such as barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and crabgrass (*Digitaria* spp.) (Akkari *et al*., 1986; Spanu *et al*., 1992; Gitsopoulos and Froud-Williams, 2004), as well as with broadleaf weeds, such as common purslane (*Portulaca oleracea* L.), field bindweed (*Convolvulus arvensis* L.), burclovers (*Medicago* spp.), black nightshade (*Solanum nigrum* L.), common cocklebur (*Xanthium strumarium* L.) and pigweeds (*Amaranthus* spp.) (Akkari *et al*., 1986; Battilani and Pietrosi, 1990; Spanu *et al*., 1992). Several studies found that barnyardgrass competition with rice increased as the depth and duration of flooding decreased (Agostinetto *et al*., 2007; Rao *et al*., 2007). Akkari *et al*. (1986) reported that control of perennial weeds like purple nutsedge (*Cyperus rotundus* L.) and johnsongrass [*Sorghum halepense* (L.) Pers.] is one of the main challenges in sprinkler irrigated rice. Okafor and De Datta (1976) have pointed out the relevance of purple nutsedge as weed in upland rice.

Herbicide weed control can be modified by the sprinkler irrigation system because the frequent irrigation events (2 to 3 per week) can wash off foliar acting herbicides from the leaves and/or activate and leach residual soil herbicides (Spanu and Pruneddu, 1998). Changes in herbicide behavior from flood to sprinkler irrigation are expected to be greater for soil residual herbicides because no standing water is present. Thus, in flood irrigated rice leaching below the root zone is usually precluded because an impervious layer is formed by tillage. Besides, soil water content is lower in sprinkler irrigated rice which could affect soil residual activity of soil applied herbicides.

Pendimethalin (N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine), dinitramine (N3,N3-diethyl-2,4-dinitro-6-(trifluoromethyl)-1,3-benzenediamine) and linuron (N'-(3,4-dichlorophenyl)-N-methoxy-N-methylurea) are soil residual herbicides which were found selective in sprinkler irrigated rice, but only pendimethalin provided an adequate weed control (Spanu *et al*., 1992). However, none of these herbicides is registered for use in rice in Spain. Clomazone (2-[(2-chlorophenyl)methyl]-4,4-dimethyl-3-isoxazolidinone), oxadiazon (3-[2,4-dichloro-5-(1-methylethoxy)phenyl]-5-(1,1-dimethylethyl)-1,3,4-oxadiazol-2-(3H)-one) and molinate (S-ethyl hexahydro-1H-azepine-1-carbothioate) are soil residual herbicides registered for use in pre-emergence (PRE) of rice. Clomazone applied PRE or in postemergence (POST) in flood irrigated rice provides good weed control of annual grasses (Jordan *et al*., 1998a; Webster *et al*., 1999; Scherder *et al*., 2004; Zhang *et al*., 2004, 2005; Talbert and Burgos, 2007), but phytotoxicity symptoms on rice plants are variable depending on cultivar and rice planting system (Zhang *et al*., 2004; Mudge *et al*., 2005a). Esqueda (2000) reported good control of grasses with clomazone in upland rice. However, there is no report of clomazone use in sprinkler irrigated rice. Oxadiazon has been used mixed with propanil (N-(3,4-dichlorophenyl) propanamide) to control weeds in sprinkler irrigated rice (Akkari *et al*., 1986), but it mostly controls broadleaf weeds (Babiker, 1982; Smith and Khodayari, 1985; Enyinnia, 1992), and crop phytotoxicity symptoms have been observed. Molinate is a volatile herbicide that needs standing water for an adequate weed control, thus it can not be used in sprinkler irrigated rice.

Ferguson and Gilmour (1979) reported difficulties in weed control in sprinkler irrigated rice when the crop was repeated during several seasons on the same site due to the increase of non controlled weeds. However, sprinkler irrigation is more flexible for rotating rice with other crops, which can favor weed control and helps avoid certain problems observed in flood irrigated rice grown in monoculture, such as barnyardgrass resistance to propanil and red rice (Baltazar and Smith, 1994).

The objective of this work was to study the selectivity and efficacy of several herbicides under sprinkler irrigated rice to establish the most adequate weed control treatments for this system.

Material and methods

Field experiments were conducted in 2003 and 2004 at Zaragoza (Spain) (Lat 42° 07' N, Long 1° 8' W). The experiments were conducted in two different fields. The soil of the 2003 experiment was a silty clay loam (20% sand, 46% silt, 34% clay) with 1.5% organic matter and a pH of 8.5. The soil of the 2004 experiment was a sandy loam (26% sand, 45% silt, 28% clay) with 1.8% organic matter and a pH of 8.4.

Rice cv. Guadiamar was planted with a commercial cereal seed drill on 28 April 2003 and 27 April 2004 in rows 0.13 m apart at a planting rate of 230 kg ha^{-1}. Plots were fertilized before planting with 54 kg N ha^{-1}, 100 kg P_2O_5 ha^{-1} and 100 kg K_2O ha^{-1}. Top dressing N was applied at tillering (50 kg N ha^{-1}) and at panicle initiation (50 kg N ha^{-1}). Plots were irrigated with a sprinkler irrigation system with sprinklers separated at 15 × 18 m and located at 1.5 m above the soil. Sprinkler water application rate was 5 mm h^{-1}. After planting, 5 mm irrigation water was applied every two days to promote the emergence of the crop. Once the crop had emerged, crop water requirements were calculated following the FAO approach (Allen *et al*., 1998). Reference evapotranspiration was calculated with the FAO Penman-Monteith method (Allen *et al*., 1998) from meteorological data obtained from an automated weather station positioned over grass and located at the experimental farm. The considered crop coefficient during the growing season was 1.2. The crop irrigation requirement was calculated weekly as the difference between crop evapotranspiration and the effective precipitation, which was estimated as 75% of the precipitation (Dastane, 1978). Precipitation during the crop season was 171 mm in 2003 and 112 mm in 2004. In 2003 the irrigation applied was 750 mm in 72 irrigation events and in 2004 the irrigation applied was 885 mm in 83 irrigation events.

Eight herbicide treatments and a control without herbicide application were compared in each year (Table 1). Treatments included herbicides applied at PRE: clomazone (Command 3ME, FMC Corporation, 1735 Market Street, Philadelphia, PA 19103, USA), oxadiazon (Ronstar EC, Bayer CropScience AG, Alfred Nobel Str. 50, D40789 Monheim am Rhein, Germany) and pendimethalin (Stomp LE, BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709, USA). Herbicides applied at POST were: azimsulfuron {N-[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]-1-methyl-4-(2-methyl-2H-tetrazol-5-yl)-1H-pyrazole-5-sulfonamide} (Gulliver, Du Pont de Nemours, Barley Mill Plaza, Walker's Mill 5-270, Wilmington, DE, USA), bentazon [3-(1-methylethyl)-(1H)-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide] + MCPA [(4-chloro-2-methylphenoxy) acetic acid] (Basagran M-60, BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709, USA) and propanil (Herbimur, Exclusivas Sarabia S.A., Camí de l'Albí-Ptda. Rec Nou s/n, 25110 Alpicat, Spain).

Results from the first year were taken into account to choose the herbicide treatments to be tested on the second year. In addition, the POST treatments tested in the second year considered the prevailing high purple nutsedge densities. Preemergence treatments were applied within seven days from rice seeding. In both years, POST treatments were applied 7 weeks after planting (WAP) (POST 1) and 10 WAP (POST 2). Herbicide treatments were applied over the crop with a N_2-pressurized backpack sprayer calibrated to deliver 300 L ha^{-1} at 200 kPa. The experimental design was a randomized complete block with 4 replications. The experimental unit area was 28 m^2 (4 × 7 m).

Tolerance of rice plants to herbicides was assessed by counting the number of emerged plants within a 0.28 m^2 grid placed randomly four times in every plot at 6 WAP, and by visually estimating crop injury at 6 WAP and at 11 WAP (2003) or at 9 and 11 WAP (2004). Crop injury was estimated through a visual integration of chlorosis, necrosis, stunting, stand reduction and tissue bleaching using a 0 to 100% scale where 0 = no injury and 100 = plant death. Weed control was evaluated at the same time than selectivity by counting the number of weeds by species within a 0.28 m^2 grid placed randomly four times in every plot. At rice harvest, weed control was assessed visually (0 to 100%

Table 1. Herbicide tolerance and rice yields in 2003 and 2004[a,b]

Herbicide (kg ai ha^{-1})		Emerged rice (plants m^{-2})	Visible injury (%)[c]				Yield (kg ha^{-1})[d]
PRE (Rate)	POST 1 and 2 (Rate)		6 WAP	9 WAP	11 WAP	Harvest	
2003							
None	None	306^{a}	0^{b}		0^{e}	0^{b}	170^{e}
None	1: Propanil (3.5) 2: Bentazon (1.6) + MCPA (0.24)	284^{a}	0^{b}		0^{e}	0^{b}	320de
Clomazone (0.36)	2: Bentazon (1.6) + MCPA (0.24)	305^{a}	32^{a}		10^{cde}	0^{b}	6,060^{a}
Oxadiazon (0.5)	2: Bentazon (1.6) + MCPA (0.24)	274^{a}	0^{b}		0^{e}	0^{b}	2,730^{bc}
Oxadiazon (0.5)	2: Azimsulfuron (0.02)	279^{a}	2^{b}		15^{cd}	0^{b}	2,170^{cde}
Pendimethalin (0.99)	2: Clomazone (0.36) + propanil (1.75)	297^{a}	2^{b}		37^{a}	0^{b}	2,620^{cd}
Pendimethalin (1.32)	2: Propanil (3.5)	234^{a}	7^{b}		5de	0^{b}	5,030^{ab}
Clomazone (0.36) + Oxadiazon (0.25)	2: Azimsulfuron (0.025)	286^{a}	25^{a}		32^{ab}	5^{ab}	6,910^{a}
Clomazone (0.36) + Pendimethalin (1.32)	2: Propanil (3.5)	216^{a}	30^{a}		22^{bc}	10^{a}	2,230^{cde}
2004							
None	None	188^{a}	0^{c}	0^{b}	0^{b}	0^{a}	0^{d}
Clomazone (0.27)	1: Bentazon (1.6) + MCPA (0.24) 2: Azimsulfuron (0.02)	174^{a}	22^{b}	7^{b}	27^{a}	12^{a}	4,400^{abc}
Clomazone (0.36)	1: Bentazon (1.6) + MCPA (0.24) 2: Azimsulfuron (0.02)	167^{a}	25^{ab}	7^{b}	30^{a}	12^{a}	5,800^{a}
Oxadiazon (0.5)	1: Bentazon (2.0) + MCPA (0.30) 2: Azimsulfuron (0.02)	163^{a}	5^{c}	0^{b}	27^{a}	7^{a}	2,550^{c}
Pendimethalin (1.32)	1: Bentazon (1.6) + MCPA (0.24) 2: Azimsulfuron (0.02)	171^{a}	5^{c}	5^{b}	25^{a}	10^{a}	3,130^{bc}
Clomazone (0.27) + Oxadiazon (0.25)	1: Azimsulfuron (0.02)	154^{a}	27^{ab}	37^{a}	25^{a}	5^{a}	5,260^{ab}
Clomazone (0.36) + Oxadiazon (0.25)	1: Azimsulfuron (0.025)	196^{a}	30^{a}	40^{a}	25^{a}	7^{a}	5,400^{ab}
Clomazone (0.36) + Pendimethalin (0.66)	1: Azimsulfuron (0.025)	211^{a}	17^{b}	40^{a}	30^{a}	5^{a}	5,360^{ab}
Clomazone (0.36) + Pendimethalin (1.32)	1: Azimsulfuron (0.02)	177^{a}	27^{ab}	42^{a}	27^{a}	7^{a}	3,980^{abc}

[a] For each year, means within a column followed by the same letter are not statistically different according to Fisher's protected LSD test at $p = 0.05$. [b] Abbreviations: PRE, preemergence; POST, postemergence; WAP, weeks after planting. [c] Crop injury was recorded on a 0 (no injury) to 100 (plant death) visual scale after PRE (6 WAP), POST 1 (9 WAP) and POST 2 (11 WAP) treatments. [d] 14% moisture content.

scale; 0 = no weed control, 100 = complete weed control) for grass weeds, broadleaf weeds and purple nutsedge separately. A value between 70 and 80 is considered as partial weed control, values between 80 and 90 are considered as moderate control, and values higher than 90 are considered as total weed control.

The rice grain from the central part of each experimental plot was harvested in October (8.4 m^2) using a 1.20 m wide combine harvester. In those plots where weed density precluded mechanical harvest, the rice grain in two squares of 1 m^2 was harvested manually. Grain moisture content was determined and the grain yield at 14% moisture content was calculated.

Data were subjected to ANOVA and means separated using Fisher's Protected LSD at $p = 0.05$. Inspection of residuals and scatterplots for the visual rating of crop injury and weed control suggested that assumptions of normality and homoscedasticity held reasonably well. Weed densities were transformed with $\sqrt{(x + 0.5)}$ before ANOVA. Means of weed densities shown on Tables 2 and 3 are non-transformed. A stepwise regression analysis was performed to determine the relevance of injury and weed control in grain yield.

Results

Rice tolerance

Rice emergence was not significantly affected by any herbicide treatment (Table 1). Pendimethalin at the highest rate reduced the rice stand by 25 to 30% in 2003 although, as stated, the difference was not significant with the rest of herbicide treated and control plots.

All treatments with clomazone applied PRE visually injured rice 6 WAP (Table 1). Injury symptoms were the typical bleaching of plants (Bollich *et al.*, 2000). The phytotoxicity symptoms of clomazone decreased with time and no injury was found at harvest. Oxadiazon and pendimethalin applied PRE as single treatment did not visually injure rice 6 WAP (Table 1). When oxadiazon was mixed with clomazone rice injury did not increase. When pendimethalin was mixed with clomazone in PRE slight visual injury was found still at harvest in 2003 (Table 1).

Early POST application of azimsulfuron (7 WAP) following PRE treatments involving clomazon, oxadiazon and pendimethalin injured rice by 37 to 42% (Table 1). In 2003, rice injury increased as the rate of azimsulfuron applied increased (Table 1). Late POST application of azimsulfuron in 2004 led to a lower rice injury than when applied earlier (Table 1). POST application of bentazon at 1.6 to 2.0 kg ha^{-1} mixed with MCPA at 0.24 to 0.30 kg ha^{-1} did not injure rice (Table 1).

Table 2. Weed control by herbicides applied to rice in 2003[a,b]

Herbicide (kg ai ha^{-1})		Weed density[c] (plants m^{-2})						Weed control (%)		
		6 WAP			11 WAP			Harvest		
PRE (Rate)	POST 1 and 2 (Rate)	CYPRO	ECHCG	SONOL	CYPRO	ECHCG	SONOL	GRAM	DICOT	CYPRO
None	None	14^{bc}	34^{a}	12^{a}	5^{a}	49^{a}	8^{a}	0^{c}	0^{d}	0^{e}
None	1: Propanil (3.5) 2: Bentazon (1.6) + MCPA (0.24)	8^{c}	20^{ab}	4^{b}	9^{a}	19^{bc}	0^{b}	2^{c}	95^{abc}	—
Clomazone (0.36)	2: Bentazon (1.6) + MCPA (0.24)	24^{ab}	0^{c}	1^{c}	1^{a}	0^{d}	0^{b}	81^{a}	95^{ab}	69^{ab}
Oxadiazon (0.5)	2: Bentazon (1.6) + MCPA (0.24)	35^{a}	3^{c}	0^{c}	1^{a}	7^{bcd}	0^{b}	37^{b}	89^{abc}	55^{bc}
Oxadiazon (0.5)	2: Azimsulfuron (0.02)	20^{abc}	9^{bc}	0^{c}	1^{a}	28^{ab}	0^{b}	37^{b}	100^{a}	93^{a}
Pendimethalin (0.99)	2: Clomazone (0.36) + propanil (1.75)	29^{a}	3^{c}	3^{b}	7^{a}	6^{bcd}	0^{b}	52^{b}	81^{c}	23^{cde}
Pendimethalin (1.32)	2: Propanil (3.5)	32^{a}	1^{c}	1^{c}	3^{a}	1^{cd}	1^{b}	76^{a}	87^{bc}	33^{cd}
Clomazone (0.36) + Oxadiazon (0.25)	2: Azimsulfuron (0.025)	27^{ab}	0^{c}	0^{c}	2^{a}	0^{d}	0^{b}	91^{a}	92^{abc}	92^{a}
Clomazone (0.36) + Pendimethalin (1.32)	2: Propanil (3.5)	39^{a}	0^{c}	0^{c}	9^{a}	0^{d}	0^{b}	87^{a}	89^{abc}	10de

[a] Means within a column followed by the same letter are not statistically different according to Fisher's protected LSD test at $p = 0.05$. [b] Abbreviations: CYPRO, purple nutsedge (*Cyperus rotundus* L.); DICOT, broadleaf weeds; ECHCG, barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.]; GRAM, grassy weeds; PRE, preemergence, POST, postemergence; SONOL, annual sowthistle (*Sonchus oleraceus* L.); WAP, weeks after planting. [c] Weed density was counted after PRE (6 WAP) and POST 2 (11 WAP) treatments.

Table 3. Weed control by herbicides applied to rice in 2004[a,b]

Herbicide (kg ai ha^{-1})		Weed density[c] (plants m^{-2})								Weed control (%)		
		6 WAP				9 WAP				Harvest		
PRE (Rate)	POST 1 and 2 (Rate)	ATXHA	CYPRO	ECHCG	SONOL	ATXHA	CYPRO	ECHCG	SONOL	GRAM	DICOT	CYPRO
None	None	2^{b}	190^{a}	42^{a}	3^{a}	4^{ab}	322^{ab}	37^{a}	4^{a}	0^{c}	0^{e}	0^{d}
Clomazone (0.27)	1: Bentazon (1.6) + MCPA (0.24) 2: Azimsulfuron (0.02)	4^{a}	204^{a}	0^{b}	1^{b}	6^{a}	175^{cd}	0^{b}	0^{b}	76^{a}	67^{c}	66^{abc}
Clomazone (0.36)	1: Bentazon (1.6) + MCPA (0.24) 2: Azimsulfuron (0.02)	1^{bc}	266^{a}	1^{b}	0^{b}	4^{ab}	322^{ab}	1^{b}	0^{b}	80^{a}	81^{abc}	81^{a}
Oxadiazon (0.5)	1: Bentazon (2.0) + MCPA (0.30) 2: Azimsulfuron (0.02)	0^{c}	247^{a}	2^{b}	0^{b}	0^{b}	389^{a}	4^{b}	0^{b}	46^{b}	99^{a}	52^{bc}
Pendimethalin (1.32)	1: Bentazon (1.6) + MCPA (0.24) 2: Azimsulfuron (0.02)	0^{c}	184^{a}	6^{b}	1^{b}	0^{b}	224^{bc}	9^{b}	0^{b}	40^{b}	91^{ab}	72^{ab}
Clomazone (0.27) + Oxadiazon (0.25)	1: Azimsulfuron (0.02)	0^{c}	223^{a}	0^{b}	0^{b}	0^{b}	122^{d}	0^{b}	0^{b}	81^{a}	87^{abc}	62^{abc}
Clomazone (0.36) + Oxadiazon (0.25)	1: Azimsulfuron (0.025)	0^{c}	169^{a}	0^{b}	0^{b}	0^{b}	92^{d}	0^{b}	0^{b}	80^{a}	83^{abc}	58^{bc}
Clomazone (0.36) + Pendimethalin (0.66)	1: Azimsulfuron (0.025)	0^{c}	151^{a}	0^{b}	0^{b}	0^{b}	104^{d}	0^{b}	0^{b}	85^{a}	90^{abc}	67^{abc}
Clomazone (0.36) + Pendimethalin (1.32)	1: Azimsulfuron (0.02)	0^{c}	182^{a}	0^{b}	1^{b}	0^{b}	122^{cd}	1^{b}	0^{b}	70^{ab}	77^{bc}	50^{c}

[a] Means within a column followed by the same letter are not statistically different according to Fisher's protected LSD test at $p = 0.05$. [b] Abbreviations: ATXHA, triangle orach (*Atriplex prostrata* Bouchér ex DC.); CYPRO, purple nutsedge (*Cyperus rotundus* L.); DICOT, broadleaf weeds; ECHCG, barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.]; GRAM, grassy weeds; PRE, preemergence, POST, postemergence; SONOL, annual sowthistle (*Sonchus oleraceus* L.); WAP, weeks after planting. [c] Weed density was counted after PRE (6 WAP) and POST 1 (9 WAP) treatments.

Propanil applied alone POST did not injure rice (Table 1). However, POST application of propanil mixed with clomazone in 2003 injured rice by 37%, which suggests that clomazone was mostly responsible for the injury (Table 1).

At rice harvest no relevant visual injury was found (Table 1). Only the mixture of clomazone at 0.36 kg ha^{-1} and pendimethalin at 1.32 kg ha^{-1} showed low (10%), but significant injury.

Weed control

The main weeds found in both years were the grass weed barnyardgrass, the broadleaved annual sowthistle (*Sonchus oleraceus* L.) and triangle orach (*Atriplex prostrata* Bouchér ex DC.), and the perennial purple nutsedge (Tables 2 and 3). Purple nutsedge at our area is typical for the old irrigated areas of the Ebro valley but is quite rare in the recently-developed irrigated areas. Given that our experimental field is within the old irrigated areas, the purple nutsedge plants found in the plots emerged from tubers.

Only clomazone applied PRE controlled barnyardgrass in both seasons while oxadiazon applied PRE did not control this grassy weed (Tables 2 and 3). Pendimethalin applied PRE provided a 76% control of grass weeds at the highest rate (1.32 kg ha^{-1}) only in one of the two years (Tables 2 and 3). When mixed with clomazone, grass weed control increased. No difference in annual weed control was found between 0.66 kg ha^{-1} and 1.32 kg ha^{-1} of pendimethalin.

When purple nutsedge density was low (< 35 plants m^{-2}, 2003) it was partially controlled (< 70%) with bentazon at 1.6 kg ha^{-1} plus MCPA at 0.24 kg ha^{-1}, and totally controlled (> 90%) with azimsulfuron (Table 2). However, at high density (> 150 plants m^{-2}, 2004) only the application of azimsulfuron provided some control (50 to 81%) of purple nutsedge (Table 3).

Rice yield

Rice yield was affected by weed control and by herbicide injury (Table 4). Weeds strongly competed with rice under sprinkler irrigation so there was almost no rice yield when no herbicide was applied (Table 1). Consequently, those treatments that did not provide an adequate weed control produced lower yield due to weed competition. The highest yields were obtained when grass weeds were adequately controlled (Tables 1 to 3) and grass weed control was the main variable related with grain yield both years (Table 4). Crop injury decreased the rice yield only in 2003 (Table 4).

In 2003, the highest rice yield was obtained with the application in PRE of clomazone at 0.36 kg ha^{-1} alone or combined with oxadiazon at 0.25 kg ha^{-1}, which adequately controlled annual weeds (> 81% at harvest) (Tables 1 and 2). In these treatments the application of azimsulfuron at 0.025 kg ha^{-1} slightly improved purple nutsedge control compared with the use of bentazon at 1.6 kg ha^{-1} mixed with MCPA at 0.24 kg ha^{-1}. The application in PRE of pendimethalin at 1.32 kg ha^{-1} and propanil in POST at 3.5 kg ha^{-1} resulted in a yield of 5,030 kg ha^{-1}, which was not statistically different to the highest yield but almost 2,000 kg ha^{-1} lower (Table 1). Rice yield in the other treatments was lower than 3,000 kg ha^{-1} due to low grass control or crop injury (clomazone at 0.36 kg ha^{-1} + pendimethalin at 1.32 kg ha^{-1} applied in PRE).

In 2004, the highest yield was less than 6,000 kg ha^{-1} probably due to the competition of purple nutsedge which was not completely controlled in any case (Tables 1 and 3). All the herbicide treatments that adequately controlled grass weeds (> 80% at harvest) produced more than 5,000 kg ha^{-1} of rice. Thus, the highest yields were obtained when clomazone was applied in PRE alone at 0.36 kg ha^{-1} or mixed with oxadiazon at 0.25 kg ha^{-1} or pendimethalin at 0.66 kg ha^{-1}. When clomazone was applied mixed with oxadiazon, rice yield was not affected if the rate of clomazone was reduced to 0.27 kg ha^{-1} (Table 1). The other PRE herbicides lead to lower rice yields due to insufficient grass weed control or due to crop injury (clomazone at 0.36 kg ha^{-1} + pendimethalin at 1.32 kg ha^{-1} applied in PRE). If grass weeds were adequately controlled with PRE applied herbicides, it was sufficient to apply azimsulfuron early POST at 0.02 kg ha^{-1} to provide an adequate control of purple nutsedge.

Discussion

Rice tolerance

The phytotoxicity symptoms of clomazone applied PRE decreased with time and no injury was found on plants at harvest, similarly to the results reported in other studies under flood irrigation (Webster *et al*., 1999; Scherder *et al*., 2004; Zhang *et al*., 2004, 2005; Mudge *et al*., 2005a) and in upland rice (Esqueda, 2000). However, some reports indicate that at high rates (> 0.8 kg ha^{-1}) rice yield can be reduced (Bollich *et al*., 2000; Mudge *et al*., 2005a). The moderate visual injury found under sprinkler irrigation agrees with the results of Jordan *et al*. (1998a) who observed lower rice injury when clomazone was applied in dry seeded rice compared to rice seeded after flooding. Mudge *et al*. (2005b) reported that when clomazone is mixed with bensulfuron or halosulfuron plant bleaching decreased without decreasing clomazone weed control. Under flood irrigation, Zhang *et al*. (2004) found cultivar differences in the rice tolerance to clomazone. Thus, long-grain cultivars were less injured than medium-grain cultivars, such as the one used in our experiment ('Guadiamar').

Although rice plants under flood irrigation have been reported to be injured by oxadiazon when applied PRE (Babiker, 1982) and POST (Smith and Khodayari, 1985), our results showed that this herbicide was

Table 4. Regression analysis of rice yield as explained by weed control and crop injury

Year	Regression equation	R^2	*p*
2003	Yield = –196 + 75.1 Control GRAM – 317 Injury at Harvest	0.82	[a]Control GRAM: 0.04; Injury at Harvest: 0.001
2004	Yield = 17.2 + 64.0 Control GRAM	0.94	Control GRAM: 0.001

[a] Control GRAM: control of grass weeds at harvest.

selective when applied PRE in sprinkler irrigated rice either alone or mixed with clomazone. Rice injury by pendimethalin has been reported under flood irrigation (Smith and Khodayari, 1985; Street and Lanham, 1996), which agrees with the injury symptoms that were found in 2003 when it was applied mixed with clomazone.

Weed control

Only clomazone applied PRE controlled grasses under sprinkler irrigation. Esqueda (2000) also found good control of junglerice [*Echinochloa colona* (L.) Link] with clomazone in upland rice but at higher rates than those used in our study. In flood irrigated rice of Arkansas (Webster and Baldwin, 1998) and Louisiana (Jordan *et al*., 1998a) clomazone provides good control of grasses and is now considered the reference herbicide for annual grasses in Arkansas (Talbert and Burgos, 2007).

Although good broadleaved weed control with oxadiazon has been reported for sprinkler irrigated rice (Akkari *et al*., 1986), upland rice (Enyinnia, 1992), and flood irrigated rice (Smith and Khodayari, 1985; Prasad and Rafey, 1995), oxadiazon applied PRE did not control grasses in our study, but improved broadleaf weed control.

Pendimethalin applied PRE provided partial control of grass weeds at the highest rate only in one of the two years. Irregular weed control of pendimethalin has been reported due to soil texture (less rapid loss in clay soil) and to lower soil persistence if not soil incorporated (Savage and Jordan, 1980; Zimdahl *et al*., 1984). Jordan *et al*. (1998b) reported incomplete control of barnyardgrass in flood irrigated rice with pendimethalin at 1.1 kg ha^{-1}.

The control of the perennial weed purple nutsedge is one of the main cultural problems of rice under sprinkler irrigation (Akkari *et al*., 1986). This weed is not common under flood irrigation conditions. Therefore, information about purple nutsedge control with the herbicides used in flood irrigated rice is scarce. When the soil remains dry for some period of the growing season, as in upland rice and dry-seeded rice, purple nutsedge has been reported as a weed of rice (Bhargavi and Reddy, 1992). It was found that when purple nutsedge density was low it was partially controlled with bentazon at 1.6 kg ha^{-1} plus MCPA at 0.24 kg ha^{-1}, but completely controlled with azimsulfuron. However, only the application of azimsulfuron provided some control of high density purple nutsedge infestations in our experiments.

Rice yield

Weed control was found to be the main cultural challenge to grow rice under sprinkler irrigation because weed control failure can result in almost complete yield loss, as in our experiments where barnyardgrass competition was particularly strong. Akkari *et al*. (1986) and Battilani and Pietrosi (1990) reported similar results. Smith (1988) indicated that barnyardgrass is a strong competitor when rice is dry seeded and field flooding is delayed. Thus, grasses should be controlled from the earliest stages of rice development in a sprinkler irrigation system.

Although pendimethalin is the recommended herbicide in Italy for rice under sprinkler irrigation (Spanu and Murtas, 2002) and adequate weed control of grass weeds has been found under flood irrigation (Baltazar and Smith, 1994; Street and Lanham, 1996), our results show less selectivity for rice compared to clomazone and oxadiazon. Thus, it would be more interesting under our growing conditions to use it at low rates (0.66 kg ha^{-1}) and mixed with clomazone to decrease rice injury and to increase the control of annual weeds.

The use of clomazone at 0.36 kg ha^{-1} is recommended as a selective and efficacious PRE treatment for weed control of annual weeds in sprinkler irrigated rice. The addition of oxadiazon at 0.25 kg ha^{-1} to clomazone at 0.27 to 0.36 kg ha^{-1} is also recommended due to the increased control of annual broadleaf weeds obtained. If only broadleaf weeds are present, the application of oxadiazon in PRE at 0.5 kg ha^{-1} would be an adequate choice. The application of azimsulfuron at 0.02 kg ha^{-1} early POST is recommended to control purple nutsedge in sprinkler irrigated rice.

Acknowledgements

This work was funded by the CICYT (AGL-1775). O. Blanco enjoyed a fellowship from the *Ministerio de Ciencia y Tecnologia* of Spain (FP2000-4783). The technical assistance of F. Arrieta, M. Izquierdo and J. Gaudo are gratefully acknowledged.

References

AGOSTINETTO D., GALON L., MORAES P.V.D., TIRONI S.P., DAL MAGRO T., VIGNOLO G.K., 2007. Interferência de capim-arroz (*Echinochloa* spp.) na cultura do

arroz irrigado (*Oryza sativa*) em funçao da época de irrigaçao. Planta Daninha 25, 689-696. [In Portuguese].
AKKARI K.H., TALBERT R.E., FERGUSON J.A., GILMOUR J.T., KHODAYARI K., 1986. Herbicides and seeding rate effects on sprinkler-irrigated rice. Agron J 78, 927-929.
ALLEN R.G., PEREIRA L.S., RAES D., SMITH M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrig Drain Pap 56. FAO, Rome.
BABIKER A.G.T., 1982. Chemical weed control in irrigated direct-seeded rice in the Sudan Gezira. Weed Res 22, 117-121.
BALTAZAR A.M., SMITH R.J., 1994. Propanil-resistant barnyardgrass (*Echinochloa crus-galli*) control in rice (*Oryza sativa*). Weed Tech 8, 576-581.
BATTILANI A., PIETROSI I., 1990. Effetti vegeto-produttivi del riso a tre regimi di irrigazione per aspersione. L'Informatore Agrario 20, 63-66. [In Italian].
BHARGAVI K., REDDY T.Y., 1992. Effect of different herbicides on population-dynamics and growth of purple nutsedge (*Cyperus rotundus*) in semidry rice (*Oryza sativa*). Indian J Agric Sci 62, 29-34.
BOLLICH P.K., JORDAN D.L., WALKER D.M, BURNS A.B., 2000. Rice (*Oryza sativa*) response to the microencapsulated formulation of clomazone. Weed Tech 14, 89-93.
DASTANE N.G., 1978. Effective rainfall in irrigated agriculture. Irrig Drain Pap 25. FAO, Rome.
ENYINNIA T., 1992. Chemical weed-control in rain-fed upland rice in Nigeria. Trop Pest Manage 38, 408-410.
ESQUEDA V.A., 2000. Control de malezas en arroz de temporal con clomazone, solo y en mezcla con propanil y 2,4-D. Agronomía Mesoamericana 11, 51-56. [In Spanish].
FERGUSON J.A., GILMOUR J.T., 1979. Water and nitrogen relations of sprinkler irrigated rice. Arkansas Farm Res 27, 2.
FLÓREZ J.A., FISCHER A.J., RAMÍREZ H., DUQUE M.C., 1999. Predicting rice yield losses caused by multispecies weed competition. Agron J 91, 87-92.
GITSOPOULOS T.K., FROUD-WILLIAMS R.J., 2004. Effects of oxadiargyl on direct-seeded rice and *Echinochloa crus-galli* under aerobic and anaerobic conditions. Weed Res 44, 329-334.
HILL J.E., SMITH R.J., BAYER D.E., 1994. Rice weed control: current technology and emerging issues in temperate rice. Aust J Exp Agric 34, 1021-1029.
JORDAN D.L., BOLLICH P.K., BURNS A.B., WALKER D.M., 1998a. Rice response to clomazone. Weed Sci 46, 374-380.
JORDAN D.L., MILLER D.K., CRAWFORD S.H., 1998b. Barnyardgrass (*Echinochloa crus-galli*) control in dry-seeded rice (*Oryza sativa*) with soil-applied and postemergence herbicide programs. Weed Tech 12, 69-73.
MUDGE C.R., WEBSTER E.P., LEÓN C.T., ZHANG W., 2005a. Rice (*Oryza sativa*) cultivar tolerance to clomazone in water-seeded production. Weed Tech 19, 907-911.
MUDGE C.R., WEBSTER E.P., ZHANG W., LEÓN C.T., 2005b. Rice (*Oryza sativa*) response to clomazone plus bensulfuron and halosulfuron. Weed Tech 19, 879-884.
OKAFOR L.I., DE DATTA S.K., 1976. Chemical control of perennial nutsedge (*Cyperus rotundus* L.) in tropical upland rice. Weed Res 16, 1-5.
PINHEIRO B. DA S., DE CASTRO E. DA M., GUIMARAES C.M., 2006. Sustainability and profitability of aerobic rice production in Brazil. Field Crops Res 97, 34-42.
PRASAD K., RAFEY A., 1995. Effect of integrated weed management on weed growth, nutrient-uptake, economics and energetics in rain-fed upland rice (*Oryza sativa*). Indian J Agric Sci 65, 260-264.
RAO A.N., JOHNSON D.E., SIVAPRASAD B., LADHA J.K., MORTIMER A.M., 2007. Weed management in direct-seeded rice. Adv Agron 91,153-255.
SAVAGE K.E., JORDAN T.N., 1980. Persistence of three dinitroaniline herbicides on the soil surface. Weed Sci 28, 105-110.
SCHERDER E.F., TALBERT R.E., CLARK S.D., 2004. Rice (*Oryza sativa*) cultivar tolerance to clomazone. Weed Tech 18, 140-144.
SMITH R.J., 1988. Weed thresholds in Southern US rice, *Oryza sativa*. Weed Tech 2, 232-241.
SMITH R.J., KHODAYARI K., 1985. Herbicide treatments for control of weeds in dry-seeded rice (*Oryza sativa*). Weed Sci 33, 686-692.
SPANU A., PRUNEDDU G., 1998. Riso irrigate per aspersione: nuove cultivar a confronto. L'Informatore Agrario 13, 64-66. [In Italian].
SPANU A., MURTAS A., 2002. Coltivazione del riso con irrigazione per aspersione. L'Informatore Agrario 7, 33-36. [In Italian].
SPANU A., PRUNEDDU G., CABRAS P., MELIS M., SPANEDDA L., 1992. Persistence and mobility in clay soil of different herbicides in sprinkler-irrigated rice. Agricoltura Mediterranea 122, 287-292.
STREET J.E., LANHAM D.J., 1996. Pendimethalin as a delayed preemergence herbicide in rice. Mississippi Agricultural & Forestry Experiment Station Research Bulletin, 1064. Available in http://msucares.com/pubs/bulletins/b1064.htm. [January 15, 2006].
TALBERT R.E., BURGOS N.R., 2007. History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Tech 21, 324-331.
WEBSTER E.P., BALDWIN F.L., 1998. Clomazone use in rice. Research Series. Arkansas Agric Exp Station 460, 91-94.
WEBSTER E.P., BALDWIN F.L., DILLON T. L., 1999. The potential for clomazone use in rice (*Oryza sativa*). Weed Tech 13, 390-393.
ZHANG W., WEBSTER E.P., BLOUIN D.C., LINSCOMBE S.D., 2004. Differential tolerance of rice (*Oryza sativa*) varieties to clomazone. Weed Tech 18, 73-76.
ZHANG W., WEBSTER E.P., BLOUIN D.C., 2005. Response of rice and barnyardgrass (*Echinochloa crus-galli*) to rates and timings of clomazone. Weed Tech 19, 528-531.
ZIMDAHL R.L., CATIZONE P., BUTCHER A.C., 1984. Degradation of pendimethalin in soil. Weed Sci 32, 408-412.